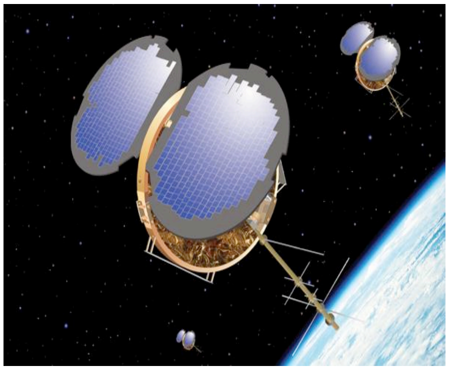
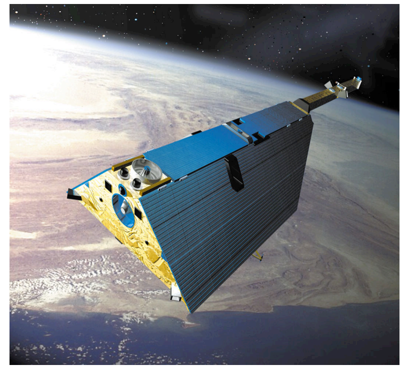


COSMIC



CHAMP

YEAR 1 ANNUAL PROJECT REPORT
NOAA GRANT NA07OAR4310224

VALIDATION AND CALIBRATION OF MSU/AMSU MEASUREMENTS AND RADIOSONDE OBSERVATIONS USING GPS RO DATA FOR IMPROVING STRATOSPHERIC AND TROPOSPHERIC TEMPERATURE TREND ANALYSIS

Principal Investigator:
Shu-peng Ben Ho (303-497-2922, spho@ucar.edu)

Co-Investigators:
Cheng-Zhi Zou ((301) 763-8042 x156, cheng-zhi.zou@noaa.gov)
Ying-Hwa Kuo ((303) 497-8910, kuo@ucar.edu)

National Center for Atmospheric Research
P.O. Box 3000, Boulder CO 80307, USA

1. Introduction

The monitoring and detecting of the vertical structure of atmospheric temperature trends are key elements in the climate change problem. Over the past decade, the roughly 30 years of the Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit (AMSU) measurements and radiosonde observations have been extensively used for climate temperature trend detection. However, due to on-orbit calibration drift for MSU/AMSU measurements, and measurement uncertainties associated with different types of radiosondes at different geophysical locations and seasons, it is extremely difficult to use MSU/AMSU and radiosonde observations to construct a long-term climate quality data set. The Global Positioning System (GPS) radio occultation (RO) is the first technique that can provide all-weather, high vertical resolution (from ~300 m near the surface to ~1.5 km at 40 km) refractivity profile. The basics of the GPS RO measurement is a timing measurement against reference clocks on the ground, which is timed and calibrated by the atomic clocks at the National Institutes for Standards and Technology (NIST). Compared to radiosonde and MSU/AMSU data, GPS RO data are not affected by weather, and don't have on-orbit calibration issue. Consequently, GPS RO data are ideally suited for use as a climate benchmark data type.

The specific goals for this project are as followings:

1. **Using GPS RO data to help identify a set of operational radiosonde networks for further climate studies.**

2. **Using GPS RO data in the stratosphere and the identified radiosondes in the troposphere as climate benchmark datasets to validate MSU and AMSU measurements to understand exactly how and why there are differences in temperature trends reported by several analysis teams using the same observation systems but different analysis methods.** The gridded vertically integrated temperatures from GPS RO data and radiosondes will also be used to evaluate the temperature records reported from RSS and UAH. The objective is to understand exactly how and why there are differences in temperature trends reported by several analysis teams using the same observation systems but different analysis methods.

3. **Generating long-term stratospheric and tropospheric climate quality temperature datasets by reprocessing nine years of AMSU/MSU data from 2001 to 2009 and delivering this data set to NCDC.**

The work undertaken to date on these project goals is detailed in section 2 and immediate plans are detailed in section 3. Plans for next year are in section 4.

2. Progress on Proposed Studies

To quantify the uncertainty of MSU/AMSU measurements and radiosonde observations for climate studies, we proposed to use GPS RO data from *Challenging Minisatellite Payload* (CHAMP) from 2002 to 2009 and FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate mission (denoted as COSMIC hereafter) from 2006 to 2009 to validate and calibrate measurements from MSU/AMSU and radiosondes. **Work to-date has focused on 1) preparation of GPS RO, radiosonde, and MSU/AMSU data for geo-location comparisons, 2) performing COSMIC-COSMIC and CHAMP-COSMIC comparisons to ensure the climate benchmark data quality, 3) assessing the quality of radiosonde measurements using GPS RO data, 4) refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data, 5) performing forward calculations using GPS RO dry temperature profiles and using the calculated brightness temperatures to validate MSU/AMSU data from $\text{NESDIS}_{\text{NEW}}$ (newly calibrated MSU/AMSU measurements using SNO method proposed by Dr. Cheng-Zhi Zou) and $\text{NESDIS}_{\text{OPR}}$ (operational MSU/AMSU observations)**.

2.1 Preparation of GPS RO, Radiosonde and MSU/AMSU Data for Geo-location Comparisons

Prior to the start of the testing the inter-comparison method for GPS RO, measurements from microwave sounders, and observations of radiosondes, two procedures were performed to prepare the data:

a. Data collection

We downloaded the following data from corresponding FTP and achieve sites:

- CHAMP data (from Jan. 2002 to Dec. 2007) from UCAR CDAAC,
- COSMIC data (from June 2006 to Dec. 2007) from UCAR CDAAC,
- MSU/AMSU data from NESDIS ($\text{NESDIS}_{\text{OPR}}$) for NOAA 14 (MSU), NOAA 15 (AMSU), NOAA 16 (AMSU) and NOAA 18 (AMSU) from 2002 to 2006,
- RSS, UAH and $\text{NESDIS}_{\text{NEW}}$ data from their related FTP sites,
- Global radiosonde data from NCAR archive, and
- ECMWF data from NCAR archive.

b. Data matching

To minimize the temporal/spatial/vertical-resolution mismatches among various datasets, we generated the following collocated data pairs:

- CHAMP-COSMIC pairs (within 15 minutes, and 50 km),
- MSU/AMSU-RO pairs (within 15 minutes, and 50 km),
- RSS/UAH-RO pairs (monthly mean, 2.5×2.5 grid),
- Radiosonde-RO pairs (temperature and moisture profiles obtained from radiosondes are interpolated onto RO locations within 3 hours and 200

km).

- ECMWF-RO pairs (ECMWF temperature and moisture profiles are interpolated onto RO locations within 3 hours and 200 km).
- To avoid AMSU vertical weighting function representation errors, instead of using a global fixed weighting function (WF), we apply a COSMIC/CHAMP dry temperature profile to an AMSU fast forward model from the Cooperative Institute for Meteorological Satellite Studies-CIMSS with 100 fixed pressure levels.

2.2 Performing the inter-GPS RO comparisons to ensure the climate benchmark data quality

Before using GPS RO data to inter-compare to MSU/AMSU and radiosonde data, we first evaluate the quality of COSMIC and CHAMP data in terms of 1) their comparability of data from different COSMIC satellites, 2) comparability of CHAMP and COSMIC RO satellite systems, and 3) reproducibility of RO processed using difference inversion procedures.

a. *Comparability of data from different COSMIC satellites*

Because in the early stage of the COSMIC mission, six COSMIC receivers were closely located, and were supposedly sensing GPS RO signals crossing similar atmospheric paths, a unique opportunity was provided to test the precision of GPS RO measurements for climate research.

- **Compare COSMIC FM3-FM4 dry temperature**: In **Fig. 1**, the differences in dry temperature (temperature derived using refractivity and hydrostatic equation assuming no water vapor in the atmosphere) between COSMIC RO soundings (from 2006, day 111 through 300) when their tangent points are less than 20 km apart were compared. The Median Absolute Deviation (MAD) is smallest from 10 km to 20 km, where the mean MAD is about 0.35 K. The mean difference (the precision for climate research) ranges 0.03 K from 0.5 km to 30 km, where near surface, the mean difference is about 0.09 K. (**Fig. 1**). The small positive FM3-FM4 dry temperature difference near the surface is mainly due to the combined effect of sampling mismatch (smaller sample pairs near the surface than those above) and larger natural variability.

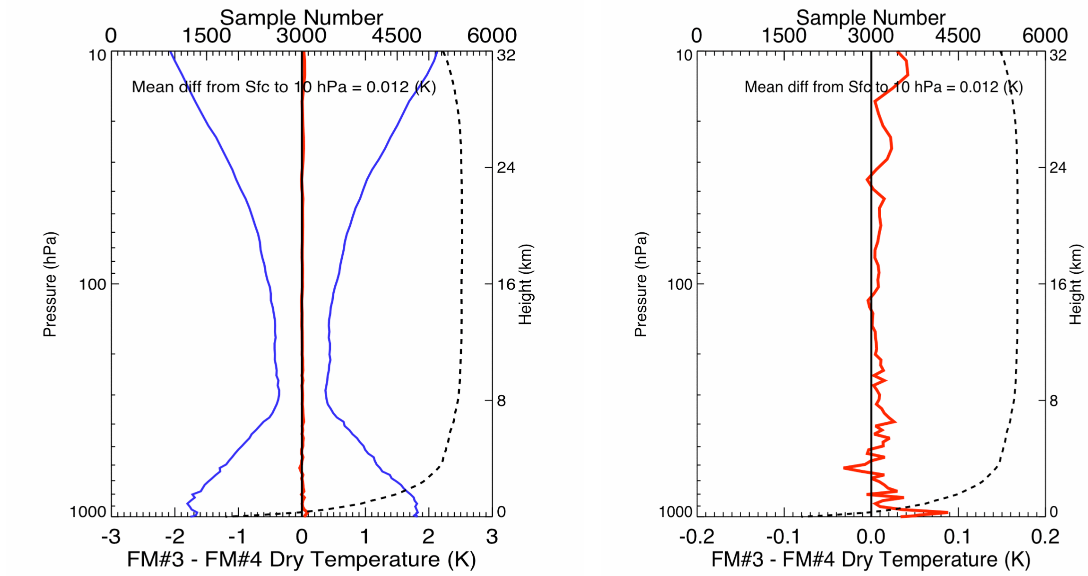


Figure 1. Panel on the left illustrates the mean and the median absolute deviation (MAD) of the dry temperature difference between two COSMIC satellites (FM3 and FM4) from 2006, day 111 through 300 where the distance between FM3-FM4 receivers is within 20 km. The dash line is MAD to its median difference (in solid line) and the dash dot line is number of FM3-FM4 profile pairs used in the comparison at various vertical levels. Panel on the right illustrates the median of the dry temperature difference between FM3-FM4 as the panel on the left but in a much smaller temperature scale in x-axis.

- **Compare COSMIC FM3-FM4 dry temperature at different latitudinal bins**: In using FM3-FM4 pairs in **Fig. 1**, contour plots of 10-degree latitudinal mean FM3-FM4 differences in dry temperature at all vertical levels (200-meter vertical resolution) over the globe (both lands and oceans), are generated in **Fig.2.** In general, the global (both lands and oceans) mean FM3-FM4 differences in dry temperature are between -0.1 K to 0.1 K from the surface to around 30 km (**Fig. 2**). Relatively large mean differences (~0.3 K) are found near tropical regions below 3 km and above 25 km and between 60°S to 80°S above 25 km, which may be primarily due to much smaller samples used (not shown) and larger MAD over these regions (not shown). Larger MAD below 8 km is related to larger natural variability (especially for water vapor) within 20 km separation distance. Though not quantifying the common systematic errors, results here still demonstrate the quality of COSMIC GPS RO data and their potential to serve as a robust climate benchmark.

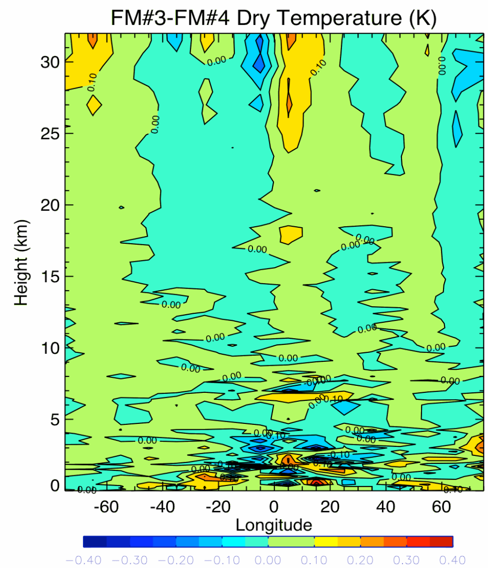


Fig. 2. Contour plots of 10-degree latitudinal mean FM3-FM4 differences in dry temperature from 80N to 80S.

- **Compare results from COSMIC FM3-FM4 dry temperature to theoretical prediction and understand the causes of the differences**
- Results found in this study are in preparation for a journal paper (**Ho, S.-P.**, Y.-H., Kuo, W. C. Schreiner, D. Hunt, C. R. Rocken, Estimates of the precision of GPS Radio Occultation for climate studies, J. Geophy. Research, 2008).

b. Comparability of CHAMP and COSMIC RO satellite systems

To use GPS RO data as a climate benchmark, it is extremely important to quantify the mean difference between these two datasets to demonstrate that the quality of GPS RO data will not change after launch.

- **Quantify the uncertainty of the difference between two RO missions for climate research:** Here the latest post-processing COSMIC and CHAMP data from 2006-2007 are inter-compared to quantify the mean difference between these two dataset to demonstrate that the quality of GPS RO data will not change after launch. **Fig. 3** depicts that the COSMIC (FM1) and CHAMP pairs collocated within 200 km and 1.5 hours collected from September 1 2006 to July 31, 2007. **Fig. 3** shows that the mean dry temperature difference between 300 hPa to 10 hPa is equal to 0.038 K.

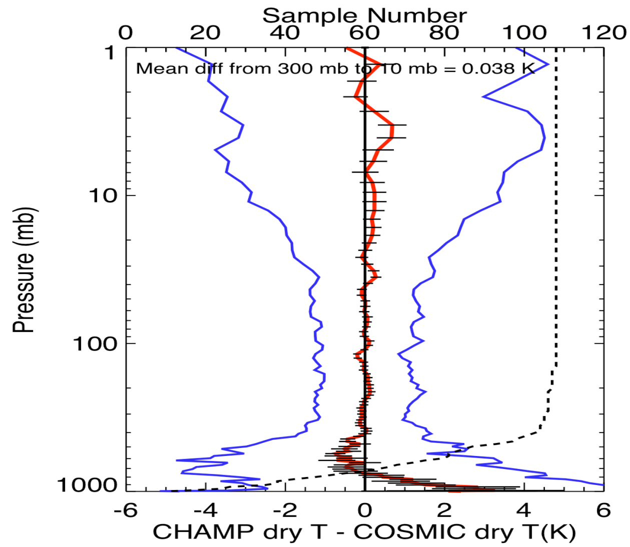


Figure 3. Comparison statistics (mean: red; standard error of the mean: horizontal black lines superimposed on the mean; standard deviation: blue, sample number of compared soundings: dotted black line) of 110 CHAMP and COSMIC profiles that were collocated within 200 km and 90 minutes within 60°N and 60°S and between 1 Sept. 2006 and 31 July, 2007.

- **Quantify the comparability of CHAMP to each COSMIC receiver and different operational modes**: The comparability of CHAMP to COSMIC data with different receivers, different operational modes (ascending and descending), and at different latitudinal bands (not shown) are examined.
- **A new approach to account for large temporal and spatial mis-match between COSMIC and CHAMP**: Due to large mis-matching between COSMIC and CHAMP RO data, only limited collocated COSMIC-CHAMP pairs are used. Therefore, a new approach is developed. We use the results from COSMIC-AMSU pairs and CHAMP-AMSU pairs to indirectly indicate the long-term stability of COSMIC and CHAMP RO data (not shown).
- **Compare results from COSMIC-CHAMP dry temperature comparison to theoretical prediction and to investigate the causes of the differences.**
- Results found in this study are in preparation for a journal paper (**Ho, S.-P.,** Y.-H., Kuo, W. C. Schreiner, D. Hunt, C. R. Rocken, Estimates of the long stability of GPS RO data: inter-comparison of COSMIC and CHAMP results, J. Geophy. Research, 2008).

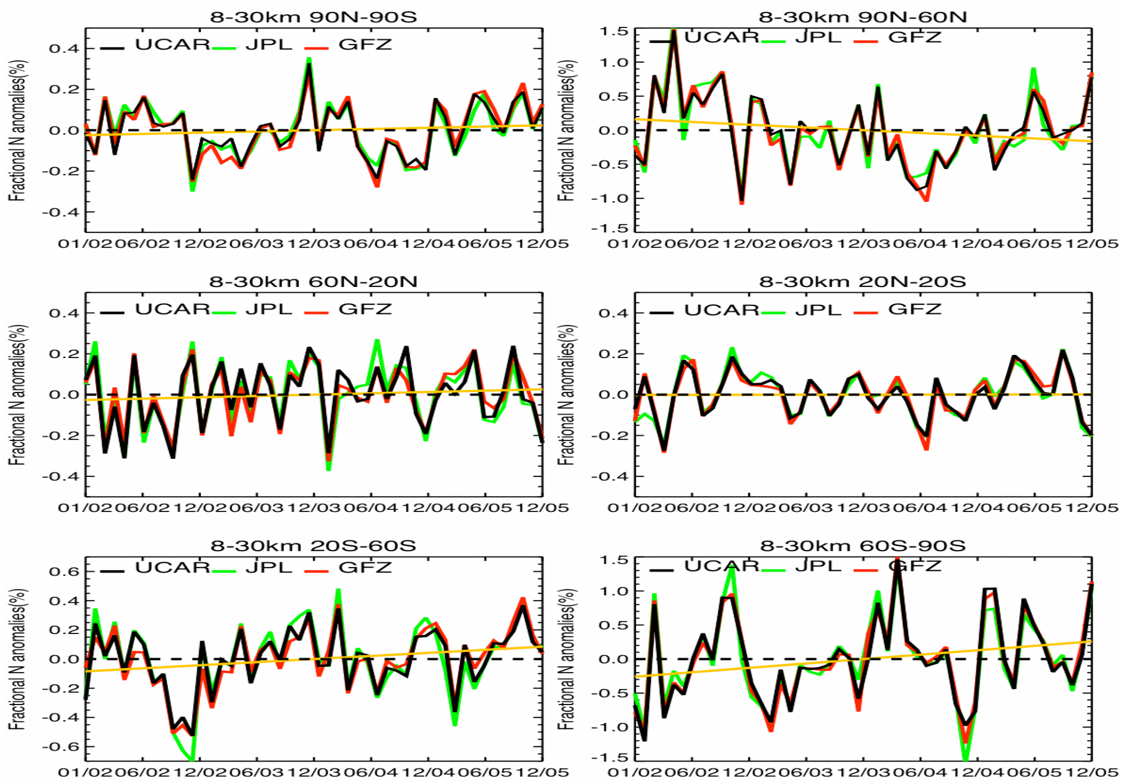


Fig. 4. The monthly mean time series of fractional refractivity anomalies are computed from the average of the N values from 8 km to 30 km for 90°N-90°S, 90°N-60°N, 60°N-20°N, 20°N-20°S, 20°S-60°S, 60°S-90°S zones. The fractional refractivity anomalies for UCAR, WEG, JPL and GFZ are computed from removing the mean seasonal cycle for the corresponding time series for each dataset, then divided by the monthly mean N values for all four datasets. The time series of the fractional refractivity anomalies for UCAR, WEG, JPL, and GFZ are in black, green, red and pink lines, respectively. The linear fit for UCAR time series is in an orange line.

c. Reproducibility of GPS RO products processed using different inversion procedures

To claim GPS RO data as climate benchmark datasets, we need to demonstrate that inverted RO products are not dependent on retrieval algorithms, where different assumptions, approximations, inversion procedures, initial conditions and quality control criteria are different from different GPS RO data processing centers.

- **Inter-compare the refractivity monthly mean climatology (MMCs) generated from different GPS RO data processing centers**: Works with scientists from Jet Propulsion Laboratory (JPL), Wegner Center (Weg-C) University of Graz, Austria, and Geo Forschungs Zentrum Potsdam (GFZ) from Germany, University of Harvard, University of Arizona, other institutions from RO community to compare refractivity derived from different data processing centers. The monthly mean climatology of refractivity are prepared and compared.

- **Quantify the time series refractivity MMC differences among different centers and understand the causes of differences:** The time series of fractional refractivity anomalies are computed from the average of the refractivity (N) values from 8 km to 30 km for 90°N-90°S, 90°N-60°N, 60°N-20°N, 20°N-20°S, 20°S-60°S, 60°S-90°S zones. The *Challenging Mini-satellite Payload* (CHAMP) refractivity profiles from 2002 to 2005 are used. The monthly mean fractional refractivity time series from each center are compared. Obvious systematic biases among different centers at different latitudinal zones are identified. Causes of difference are identified.
- **Conduct the trend analysis using refractivity MMC from different centers: Fig. 4** shows that even with different initial conditions, assumptions, approximations, and inversion algorithms, and quality control criteria used by different centers, their time series of the fractional refractivity anomalies are highly consistent to each other. The uncertainty of the trend for refractivity fractional anomalies is within **±** 0.045%/5 yrs, which is about **±** 0.06 K/5 yrs. The small trend difference is mainly caused by the different sampling numbers used by different centers, which results in different quality control criteria being applied in the data binning process.
- **Conduct sampling error analysis and quantify the cause of the uncertainty of the trend difference among MMCs from different centers.**
- Now I am leading the efforts to coordinate the progress of this task among different centers and am preparing results to present to climate and RO communities in a journal paper (**Ho, S.-P.,** Gottfried Kirchengast, Stephen Leory, Chris Rocken, Ying-Hwa Kuo, Jens Wickert, Tony Mannucci, Sergey Sokolvskiy, William Schreiner, Doug Hunt, Andrea Steiner, Ulrich Foelsche, and Chi Ao, 2008: Estimates of the Uncertainty for using Global Positioning System Radio Occultation Data for Climate Monitoring: Inter-comparisons of Refractivity Derived from Different Data Centers, J. of Climate, 2008).

2.3 Evaluate the quality of radiosonde measurements using GPS RO data and quantify the precision and accuracy of RO data in the lower troposphere

a. The usefulness of GPS RO to evaluate the quality of different types of radiosonde systems

Globally, there are roughly 850 radiosonde stations using about fourteen different types of radiosonde systems. All radiosonde systems have known observational

Region	Sonde Type	#of Match	Del Nradio/ Absolute mean (S.D.) (%)	Del Necmwf/ Absolute mean (S.D.) (%)	Del Tradio/ Absolute mean (S.D.) (K)	DelTecmwf /Absolute mean (S.D.) (K)	DelWradio /Absolute mean (S.D.) (g/kg)	DelWecmwf /Absolute mean (S.D.) (g/kg)
Russia	Mars	2000	0.0/0.2 (1.33)	-0.14/0.18 (0.73)	-0.28/0.3 (1.9)	-0.04/0.11 (0.6)	**-0.03**/0.08 (0.57)	0.0/0.04 (0.32)
Japan	MEISEI	125	0.13/0.2 (1.53)	0.08/0.2 (0.91)	0.15/0.23 (1.88)	-0.11/0.16 (0.62)	**0.07**/0.09 (0.83)	0.06/0.09 (0.53)
China	Shang	625	**0.07/0.46 (1.43)**	**-0.04/0.20 (0.9)**	-0.2/0.37 (1.7)	-0.11/0.16 (0.55)	**0.25/0.34 (0.85)**	**0.03/0.13 (0.48)**
Others	Vaisala	3000	0.08/0.18 (1.6)	-0.02/0.09 (0.81)	-0.01/0.1 (1.78)	-0.03/0.08 (0.6)	**0.11**/0.11 (0.61)	-0.0/0.034 (0.37)

Table 1. Mean difference, mean absolute fractional difference, and standard deviation (S.D.) of refractivity (%), temperature (K) (from surface to 25 km) and water vapor (g/kg) (from surface to 10km) between COSMIC RO soundings and the soundings from four regions with several types of radiosonde system (in the boxes with red background). The statistical comparisons between COSMIC refractivity (%), temperature, and water vapor to those from collocated ECMWF analysis at regions of those different types of radiosonde are also compared (in the boxes with green background).

errors, and are dependent upon the type of sensors. To use radiosondes as climate benchmarks, it is necessary to validate their accuracy at different vertical atmospheric layers against a global standard reference.

- **Differentiate the quality of different types of radiosonde systems using COSMIC**: To see if GPS RO refractivity at lower troposphere is of sufficiently high accuracy to differentiate the performance of different types of radiosondes, we compare COSMIC refractivity, derived temperature and water vapor (WV) profiles to the same parameters derived from collocated radiosonde and ECMWF analysis. COSMIC refractivity, derived temperature and humidity profiles that occur within 2 hours and 300 km of radiosonde profiles are used from July 2006 to Oct. 2006. During this period no COSMIC data were simulated into the ECMWF analysis. Comparison results are summarized in **Table 1.**
- **Analysis results**: In general, we did not find significant variation of the quality of the RO soundings over different geographical areas. This is evidenced by the relatively small variations (in terms of absolute fractional difference) in the RO and ECMWF differences between geographical areas. On the other hand, we found obvious COSMIC-radiosonde mean

absolute bias over China, which is mainly below 8 km (not shown). No obvious fractional N biases are found over the same regions for COSMIC-ECMWF fractional refractivity (%N). With the open-loop technique, COSMIC RO signals penetrate much deeper than those from CHAMP. Because N is very sensitive to water vapor in the lower troposphere, much of N information is used for water vapor retrievals. Therefore, with larger N bias over China (than other regions), we also find larger WV bias over China. Conclusions drawn from this study are: **i) because the quality of RO soundings is independent of geographical location, COSMIC RO data can be used to differentiate the quality of different types of radiosonde systems; ii) because retrieval results from 1D-var algorithm fit better to measurements than the first guess, and N is more sensitive to water vapor, the 1D-var water vapor retrievals are insensitive to the first guess fields of temperature and moisture; iii) the N bias in the lower troposphere is mainly caused by the moisture bias.**

- Results found in this study are in preparation for a journal paper (**Ho, S.-P.,** Y.-H., Kuo, Using COSMIC RO data to quantify the quality of Radiosonde data. JRL, 2008**).**

b. Assessing the Precision and Accuracy of GPS RO measurements in the Lower Troposphere: 1D-var water vapor vs. ECMWF water vapor

With the high precision N from GPS RO data and reasonable independent temperature profiles, we can have highly accurate water vapor profiles.

- **Quantify the uncertainty of COSMIC 1D-var water vapor profiles**: To quantify the uncertainty of COSMIC 1D-var water vapor profiles, which were derived using NCEP global analysis as the first guess, we compare them with the global collocated water vapor profiles from ECWMF.
- **Analysis results:** Early results show that COSMIC 1D-var water vapor profiles are very consistent with those from ECMWF (not shown). Over mid- and high- latitudes, the mean WV difference between COSMIC and ECMWF is very close to zero. The largest WV difference is over the Tropical regions near the surface. The WV difference is around 0.4-0.8 g/kg, which is within 5% of the mean water vapor profile over the tropics.
- Results found in this study are in preparation for a journal paper (**Ho, S.-P.,** Y.-H., Kuo, Global Comparisons of COSMIC WV using ECMWF and Radiosonde data, J. Geophy. Research, 2008).

2.4 Refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data

Before using GPS RO data to recalibrate MSU/AMSU data, we need to refine the calibration methods by demonstrating 1) the usefulness of RO data for climate research, 2) the usefulness of GPS RO data to inter-calibrate MSU/AMSU measurements, and 3) the usefulness of GPS RO data to identify the on-orbital location/time dependent AMSU/MSU biases.

a. The Usefulness of RO Data for Climate Research

To demonstrate that although with much smaller number of observations than MSU/AMSU measurements, the monthly mean lower stratosphere temperature (TLS) derived from CHAMP GPS RO is very consistent with those obtained from the microwave measurements.

- **Comparison of CHAMP derived TLS with those from UAH and RSS**: The microwave brightness temperature (Tb) for the Lower Stratosphere (TLS, e.g., $CHAMP_{TLS}$) datasets provided by Remote Sensing System (RSS, e.g., RSS_{TLS}) and University of Alabama in Huntsville (UAH, e.g., UAH_{TLS}) are compared with the GPS radio occultation (RO) data from *Challenging Mini-satellite Payload* (CHAMP) over 49 months from June 2001 to June 2005.
- **Analysis results**: The results generally demonstrate excellent agreement of monthly mean Tb between RSS_{TLS} and UAH_{TLS} to that of $CHAMP_{TLS}$ data on the 10 degree × 10 degree grids. The $CHAMP_{TLS}$ matches better with that of RSS_{TLS} in terms of variations (higher correlation coefficient and smaller standard deviations) and matches better with that of UAH_{TLS} in terms of mean. RSS_{TLS} is systematically 0.8 K to 1.9 K lower than that of $CHAMP_{TLS}$ at almost all latitudinal zones except for the 20°S to 60°S zone. Because CHAMP RO has only one GPS receiver, it will take more than three months to provide complete coverage for diurnal cycle sampling over a region in the low and middle latitudes, therefore in this study, we may not have enough GPS RO observations to determine the small difference during this period in RSS_{TLS} and UAH_{TLS} due to different diurnal correction algorithms used from these two groups
- Results from this study are submitted and accepted by GRL (**Ho, S.-P.**, Y. H. Kuo, Zhen Zeng and Thomas Peterson, A Comparison of Lower Stratosphere Temperature from Microwave Measurements with CHAMP GPS RO Data, Geophysical Research Letters, VOL. 34, L15701, doi:10.1029/2007GL030202, 2007)

b. The Usefulness of GPS RO to Inter-calibrate MSU/AMSU Measurements

To demonstrate the usefulness of GPS RO data to inter-calibrate MSU/AMSU measurements, we collect GPS RO-AMSU pairs within 15 minutes and 50 km and generate the calibration coefficients (slope and offset) and examine the uncertainty of the calibration coefficients. GPS RO dry temperature profiles are converted to AMSU brightness temperature using the CIMSS AMSU forward radiative transfer model.

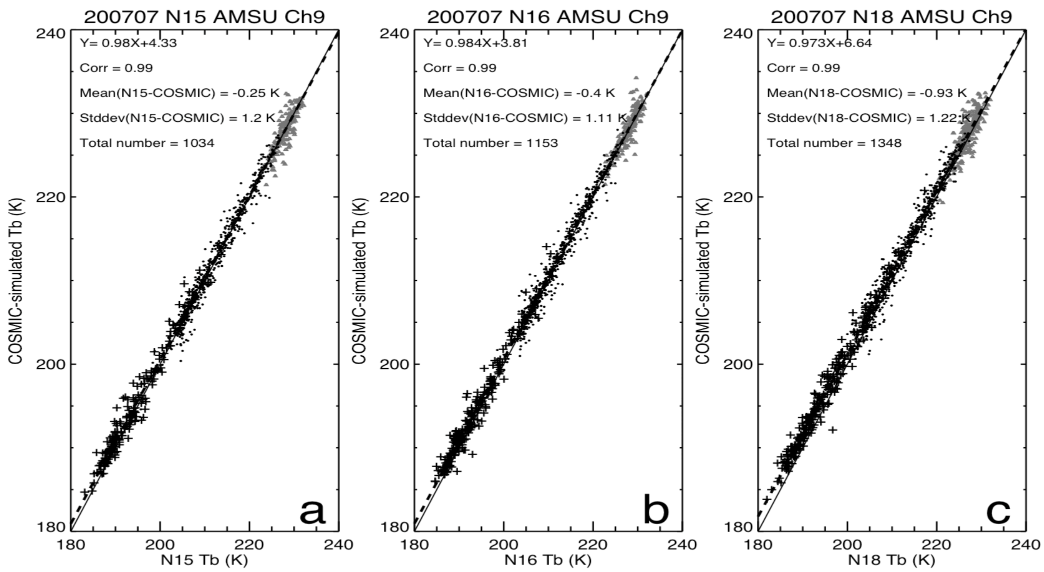


Fig. 5. Comparison of COSMIC-simulated AMSU Ch9 Tbs and (a) N15 AMSU Ch9 Tbs, (b) N16 AMSU Ch9 Tbs, and (c) N18 AMSU Ch9 Tbs for July 2007. Pixels in gray triangles are from the 60°N-90°N zone, pixels in dark dots are from the 60°N-60°S zone, and pixels in dark crosses are from the 60°S-90°S zone. The best fit is in dashed line. Diagonal one-to-one fit is in solid line.

- **Comparison of GPS RO simulated brightness temperatures (Tbs) and AMSU Tbs**: The comparisons are made between COSMIC-simulated AMSU Ch9 Tbs and collocated AMSU Ch9 Tbs from N15, N16 and N18 within 15 minutes and 50 km.
- **Analysis results**: The comparisons between COSMIC-simulated AMSU Ch9 Tbs and collocated AMSU Ch9 Tbs from N15, N16 and N18 within 15 minutes and 50 km are shown in Figs. 5a, b, and c, respectively. The figures show that COSMIC synthetic AMSU Tbs for N15 (Tb_{COSMIC_N15}), N16 (Tb_{COSMIC_N16}) and N18 (Tb_{COSMIC_N18}) are highly correlated with Tb_{AMSU_N15} (correlation coefficient=0.99), Tb_{AMSU_N16} (correlation coefficient=0.99) and Tb_{AMSU_N18} (correlation coefficient=0.99), respectively, and with small standard deviation to their means of COSMIC-N15 (1.20 K), COSMIC-N16 (1.11 K) and COSMIC-N18 (1.22 K) pairs. This demonstrates the usefulness of COSMIC RO data for inter-calibrating AMSU Tbs.
- Results from this study combined with other analysis are submitted and accepted by TAO (**Ho, S.-P.,** M. Goldberg, Y.-H. Kuo, 2007: The application of COSMIC data for improving stratospheric temperature trend analysis : the preliminary results, TAO, in press)**.**

	60°N–90°N	60°S–90°S
N15-COSMIC	-0.05K	-0.73K
N16-COSMIC	-0.22K	-0.83K
N18-COSMIC	-0.55K	-1.50 K
N15-N16	0.03 K (0.17 K)	0.09 K (0.1 K)
N16-N18	0.47 K (0.33 K)	0.57 K (0.67 K)
N15-N18	0.5 K (0.5 K)	0.69 K (0.77 K)

Table 2. The mean Tb biases for N15-COSMIC, N16-COSMIC, N18-COSMIC, N15-N16, N16-N18 and N15-N18 pairs over 60°N–90°N and 60°S–90°S zones. NOAA-NOAA biases inferred from NOAA-COSMIC are listed in parentheses.

c. The Usefulness of GPS RO data to Identify the On-orbital Location/Time Dependent AMSU/MSU Biases

Different MSU/AMSU missions may contain different measurement biases, which actually vary with time and location due to on-orbit heating or cooling of the satellite component. This causes great difficulties for climate trend detection. Here we demonstrate the usefulness of GPS RO data to inter-calibrate AMSU brightness temperatures (Tbs) by identifying the orbit-dependent biases for:

- **Comparison of GPS RO simulated brightness temperatures (Tbs) and AMSU Tbs at different geo-locations:** COSMIC RO dry temperature profiles from July 2007 are used to compute the synthetic AMSU Ch9 Tbs. COSMIC-simulated AMSU Ch9 Tbs and collocated AMSU Ch9 Tbs from N15, N16 and N18 within 15 minutes and 50 km are compared. To see if the NOAA-COSMIC biases are consistent with AMSU inter-satellite biases from different missions, AMSU Ch9 Tbs for N15-N16, N16-N18 and N15-N18 pairs are also generated. For NOAA polar satellites, the collocated N15-N16, N16-N18 and N15-N18 pairs within 50 km and 15 minutes all occurred only over polar regions.

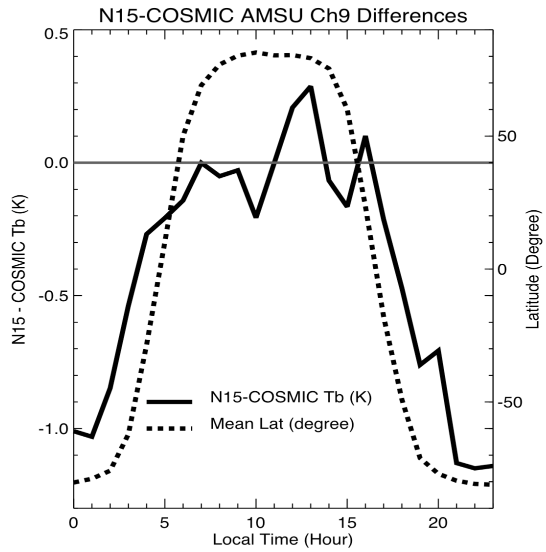


Fig. 6 Binned N15-COSMIC AMSU Ch9 Tb differences for each local time and binned latitude variation for N15 orbit for each local time. The gray solid line is for N15-COSMIC AMSU Ch9 Tb=0 for different local time.

- **Analysis results**: COSMIC-NOAA pairs at the 60°N–90°N zones, the 60°S–60°N zone, and the 60°S–90°S zone and list the mean AMSU Ch9 Tb biases for N15-COSMIC, N16-COSMIC and N18-COSMIC pairs over the 60°N–90°N and the 60°S–90°S zones are listed in **Table 2**. It shows that the mean AMSU inter-satellite biases are consistent with those for COSMIC-AMSU pairs. The mean N15-N16, N16-N18 and N15-N18 Tbs at both the 60°S–90°S and 60°N–90°N regions can almost always be reproduced using Tb biases of NOAA-COSMIC pairs. We plot the binned N15-COSMIC AMSU Ch9 Tb differences for each local time and binned latitude variation for N15 orbit for each local time in **Fig. 6.** It shows that N15-COSMIC Tbs are in general lower during the southern hemispheric winter where N15 is under the shadow of the earth (solar zenith angle is larger than 80 degrees) and are higher in the northern hemisphere (ranges from 7 to 17 local times). Because GPS RO data are not affected by the temperature variation of the satellite component, the mean N15-COSMIC AMSU Tb biases are mainly from AMSU Tb anomalies due to the heating or cooling of the satellite component.

- Results from this study and combined with other analysis are submitted and accepted by OPAC-3 special issue (**Ho, S.-P.,** Y.-H. Kuo, 2008: Construction of consistent Climate dataset using GPS RO data and AMSU measurements, proceeding of OPAC-3, in press).

2.5 Other related Work

In addition to testing and refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data, I have also worked with UCAR COSMIC team to summarize the early results from the COSMIC mission and publish the results in journal papers. I have also worked with NOAA scientists, scientists in RO communities and climate communities to demonstrate the usefulness for GPS RO data for climate research. These collaborations have an influential impact on stimulating NOAA's interests in a COSMIC follow up mission and on promoting GPS RO for climate applications to the climate community. I have also presented above results at several workshops and conferences. Related activities are summarized as the followings:

- **Summary of the weather, climate, space weather applications of COSMIC in a BAMS paper:** Anthes, R. A., P. Bernhardt, Y. Chen, L. Cucurull, K. Dymond, D. Ector, S. Healy, **S.-P. Ho**, D. Hunt, Y.-H. Kuo, H. Liu, K. Manning, C. McCormick, T. Meehan, W. Randel, C.R. Rocken, W. Schreiner, S. Sokolovskiy, S. Syndergaard, D.Thompson, K. Trenberth, T.-K. Wee, Z. Zeng, The COSMIC/FORMOSAT-3 Mission: Early Results, *Bul. Amer. Meteor. Sci. March,* 2008.
- **Summary of the first 18 months of COSMIC in the TAO special issue:** Kuo, Y. H., et al. The FORMOSAT-3/COSMIC Mission: Eighteen Months after Launch, TAO, 2008 (in press).
- **Ho, S.-P.**, Applications of COSMIC Radio Occultation Data to Climate Monitoring: Early Results, NOAA, Camp Springs, MD, July 13, 2007.
- **Ho, S.-P.**, Applications of COSMIC Radio Occultation Data to Climate Monitoring: Early Results, the 3rd international workshop on Occultation for Probing Atmosphere and climate, Graz, Austria, Sep. 17-21, 2007.
- **Ho, S.-P.**, Inter-comparisons of Refractivity and Dry Temperature Derived from different Data Center, COSMIC-workshop, Boulder, CO., Oct. 22-24, 2007.
- **Ho, S.-P.**, GPS RO-MSU calibration and data record, 2008: NOAA-NIST Workshop on Calibration for Climate-Quality Time Series, Camp Springs, MD, Jan 14, 2008 (invited talk).
- **Ho, S.-P.**, Applications of COSMIC Radio Occultation Data to Climate Monitoring: Early Results, AMS, New Orleans, LA., 20-24 January 2008 (invited talk).
- **Ho, S.-P**, Construction of Consistent Temperature Records using Global Positioning System Radio Occultation Data and Microwave Sounding Measurements, COSMIC meeting in AMS, New Orleans, LA., 20-24 January 2008.

- **Ho, S.-P.**, Comparability and reproducibility of RO data, Workshop on the Applications of GPS Radio Occultation to Climate, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008. (invited talk)
- Rocken C., S. Sokolovskiy, W. Schreiner, D. Hunt, **S. P. Ho**, Y.-H., Kuo, U. Foelsche, Climate Monitoring with Radio Occultation Data: systematic error sources, Workshop on the Applications of GPS Radio Occultation to Climate, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008.
- Sokolovskiy S., C. Rocken, W. Schreiner, D. Hunt, **S.-P.Ho**, Y.-H.Kuo, S. Syndergaard, U.Foelsche, Climate Monitoring with Radio Occultation Data: Effects and magnitudes of some specific errors of GPS RO data and assumptions used in their processing, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008.
- Help to organize the Workshop on the Applications of GPS Radio Occultation to Climate, NCAR Foothills Laboratory, Building #1 Atrium Conference Room 3450 Mitchell Lane, Boulder, CO 80301 March 17-18, 2008.
- Interact with NOAA scientists and scientists from international RO community on several special issues related to use GPS RO data for climate researches. In charge of organizing related responses from UCAR and RO community to NOAA scientists.
- Many above presentations, published/submitted manuscripts can be found in http://www.cosmic.ucar.edu/~spho/

3. Immediate Plans for the Remainder of Calendar Year 2008

Since I have completed the **Preparation of GPS RO, Radiosonde data, and MSU/AMSUMOPITT data for Geo-location Comparisons** and **Testing and refining the methods to use GPS RO data to inter-compare and inter-calibrate MSU/AMSU data** are complete, immediate plans for the remainder of this calendar year (from May to August 2008) will include **1) preparation of manuscripts described above, and 2) using GPS RO data to validate MSU/AMSU data from NESDIS$_{\mathbf{NEW}}$ and NESDIS$_{\mathbf{OPR}}$.**

a. Preparation of manuscripts

Preparation of manuscripts detailing:

- Comparability of data from different COSMIC satellites (Section 2.2.a)
- Comparability of CHAMP and COSMIC GPS satellite systems (Section 2.2.b)
- Reproducibility of GPS RO products processed using different inversion procedures (Section 2.2.c)
- The usefulness of GPS RO to indentify the quality of different types of radiosonde systems (Section 2.3.a)

- Potential for high precision and accuracy in the lower troposphere: 1D-var water vapor vs. ECMWF water vapor (Section 2.3.b)

b. Using GPS RO data to validate MSU/AMSU data from $NESDIS_{NEW}$ and $NESDIS_{OPR}$

In addition to the work described in Section 2.4, we will also continue:

- Performing forward calculation using GPS RO dry temperature profiles and using the calculated brightness temperatures to validate MSU/AMSU data from $NESDIS_{NEW}$ and $NESDIS_{OPR.}$
- Preparation of a manuscript detailing the method and results for the GPS RO and $NESDIS_{NEW}$ and $NESDIS_{OPR}$ comparisons.

4. Plans for the Calendar Year 2009

In 2008, we plan to continue to use GPS RO data to validate and calibrate MSU/AMSU measurements and radiosonde observations and focus on the specific goal 2, and 3 for this project as mentioned in section 1.